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LHCb-2008-049

The LHCb Silicon Tracker: lessons learned (so far)

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Abstract

The LHCb Silicon Tracker is part of the main tracking system of the LHCb detector. It covers the full acceptance of the experiment in the Tracker Turicensis (TT) in front of the dipole magnet and the innermost part in the three Inner Tracker (IT) stations downstream of the magnet. We report on final elements of the production, the installation and commissioning process in the experiment. Focusing on electronic and hardware issues we describe the lessons learned and the pitfalls encountered. First experience of detector operation is presented.

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I. Overview

The Silicon Tracker of the LHCb experiment [2] consists of silicon strip detectors with a pitch of around 200 µm. For the TT station upstream of the magnet, a 500 µm thick sensor with 512 strips is used, while the three IT stations after the magnet feature 320 and 410 µm thick sensors of 384 strips each. This adds up to 143k readout channels for the TT station and 129k channels for IT. The signals are amplified and processed by the Beetle readout chip [3], which transmits its data via differential analogue lines to the Service Boxes. The Service Boxes are located outside the acceptance of the tracking system to minimize the amount of dead material. For the TT station, they are mounted to the upstream face of the LHCb dipole magnet while the IT Service Boxes are fixed to the lower end of the support frames of each tracking station. Digitizer Boards inside these boxes digitize and convert the analogue signals into optical signals which are transmitted via fiber of up to 120 m length to the counting house [4].

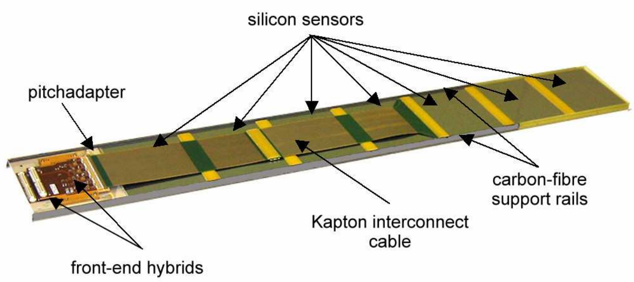

Figure 1: Photo of a TT halfmodule

This paper focuses on some of the problems encountered during construction and installation of the on-detector components and electronics and the solutions implemented. The described problems are located on the silicon sensor modules, the cable connection area just outside the acceptance angle of the detector and in the Service Boxes and will be discussed in the following sections.

II. Silicon Sensor Modules

A. Conductive (Silver) glue

Conductive glue was used to connect the grounding of the TT readout hybrid to the cooling block of the sensor module and for the connection of the biasing voltage on the back side of each silicon sensor. While initial testing showed a good connection, older prototypes suffered from high glue resistances. The reason is due to the inability of the silver glue to stop the oxidization for the underlying aluminium [5]. In addition the grounding of the readout hybrid suffered from thermal cycling (Fig. 2). It was therefore decided to change the connection procedure for these locations. The grounding of the readout hybrids was changed to a screwed solder lug. As no soldering is possible on the back side of a silicon sensor, the bias lines of the Kapton supply cables were bonded to the sensor followed by a glob-top seal to protect the bond wires.

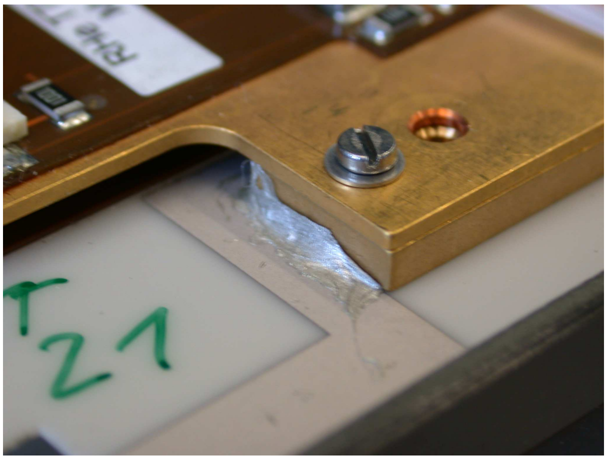

Figure 2: Breakup of silver glue after thermal cycling

B. 4^{th} channel problem

A problem that was discovered very recently concerns the wire bonds at the inputs of the Beetle front-end chips. As shown in Fig. 3, these are executed in four bond-rows to match the four-fold staggered input pads of the Beetle. A few weeks after the installation of the detector modules in the experiment it was found on six out of the 280 installed readout hybrids that a significant number of bonds in the inner-most of these bond rows were broken. Nothing similar had ever been observed in the extensive burn-in tests that each module had to pass during its construction and that were designed to reproduce conditions in the experiment as closely as possible. As of now, we have no explanation for this effect, investigations are ongoing.

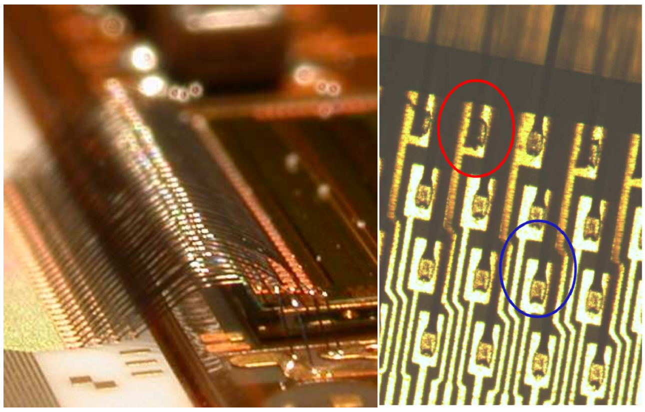

Figure 3: 4-fold staggered bonding (left) and comparison of good vs. bad bond connections (right)

III. Cable connections

The Beetle readout chips amplify the signals from the silicon sensors and transmit the analogue signals upon a Level-0 trigger to the Service Boxes. This transmission is done via electrical cables. For the TT station, the first 70 cm are done via flexible Kapton cables to minimize the cross section which has to be routed through the thermal isolation of the detector box. Directly outside of the cold volume, the Kapton cables are then connected via small patch panels to 8 m long multi-conductor round cables. These cables then connect to the Service Boxes which are located at the magnet return yoke outside the tracking volume.

A. High density connectors

Each readout hybrid requires a single cable connection only, where all necessary supplies and signals are provided. An 80-pin high-density connector was chosen which connects on the Beetle readout hybrid inside the cold volume and to small patch panels outside. Due to the mechanical layout, the inner ends of the cables are guided by small gaps in the main cooling plate. Therefore no torque applies to this mating interface. As space is very limited on the outside between the feedthrough and the patchpanels, the cables had to be bent in tight radii to be mated to the patch panels. The resulting torque led in several cases to unreliable electrical connection between mated high-density connectors. To ensure a mechanical fix of this mating, milled aluminium clamps were designed which could be applied to the patch panel stack and improved the connection (Fig. 5).

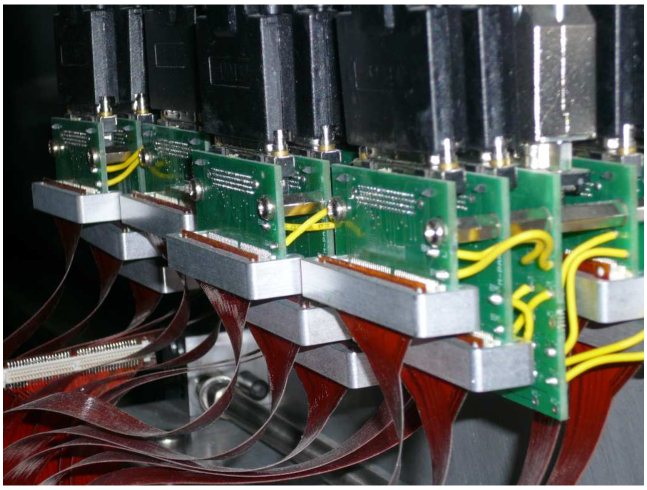

Figure 4: machined aluminium clamps for securing the high-density connectors

B. *Kapton cable cracks*

Another result of the required tight radii were cases of hairline cracks on the boundary of the rigid soldered pins of the high density connectors to the thin signal traces on the flexible Kapton cable. This is a well known problem and could have been avoided by a rigid support under the solder joints together with a gradual thinning of signal traces to avoid width discontinuities. Due to the small trace width and the flexible Kapton substrate, the only repair option is to replace an affected cable. As no mechanical movement is involved after installation, no system-wide replacement of this cable type is currently foreseen.

IV. Electronic Design Issues

The following section describes problems with electronic design issues. These problems are located on the Digitizer Board, which digitizes the analogue signal and serializes the data for optical transmission, as well as on the backplane which provides power, timing and control signals to the Digitizer Boards.

A. *Fast ADC bandwidth*

In early laboratory tests, a non-flat noise distribution within a analogue readout frame was discovered. As this distribution was persistent even without any attached readout chip, it was traced back to have its origin inside the Digitizer Board itself.

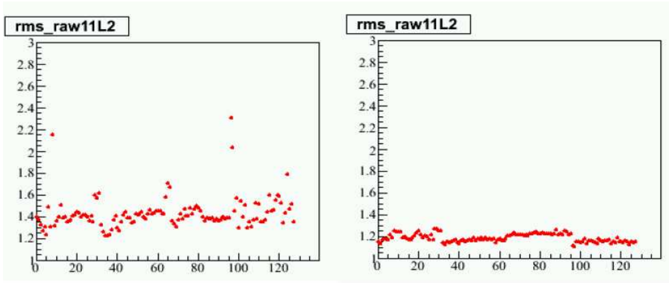

Figure 5: Comparison of raw noise without filter (left) and with filter (right)

In addition to the sampling rate, any ADC has a specified analogue bandwidth. Usually, this bandwidth exceeds the sampling rate to enable ‘undersampling’, i.e. to digitize a signal with a frequency larger than the sampling rate. To limit the amount of noise at the input of an ADC, a lowpass filter with a properly dimensioned cutoff frequency has to be used. While an early datasheet of the used ADC cited an analogue bandwidth of 100 MHz [6], an updated version listed a bandwidth of 1000 MHz [7]. Tests have shown that a 70 Mhz lowpass, which could be easily added to the existing layout, was sufficient to restore the required flat noise distribution (Fig. 6). This lowpass filter was fitted to all Digitizer Boards prior to installation in the detector.

B. *VCSEL mounting*

The Digitizer Board design uses the CERN GOL chip [8] to encode the digitized physics data into a serialized bitstream. To make use of the internal laser driver of the GOL, single VCSEL diodes were mounted directly next to each GOL chip. These VCSEL diodes are glued into a metal receptacle with threaded holes to provide mechanical fixation to the printed circuit board as well as optical alignment with an attached fiber (Fig. 7).

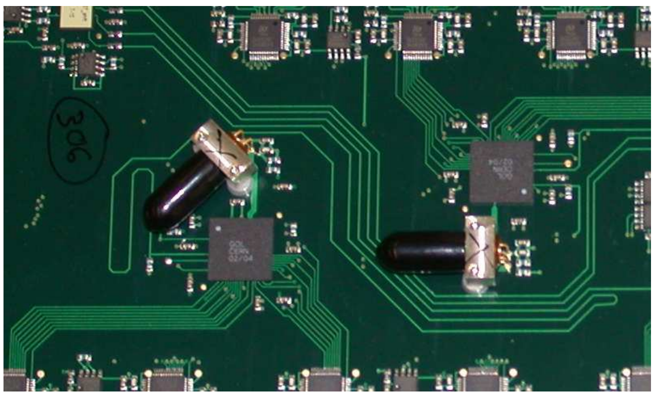

Figure 6: VCSEL diodes with receptacle next to GOL serializer

During reception tests of the production Digitizer Boards, 30 % of the VCSEL diodes were determined to be outside of the optical power specifications. Tests performed by the vendor confirmed a misalignment of the VCSEL diodes inside the metal receptacle. This problem was traced to the soldering procedure of the diodes, which were wave soldered. As the diodes were already fixed to the board via their screws, a large amount of heat was transferred through them into the receptacle which led to the weakening of the glue holding the diode in alignment. As the preproduction boards were hand-soldered, this problem did not show up during the first batch of boards. A repair of these diodes was not possible and therefore all boards had to be screened and the defective diodes were individually replaced.

C. *Slow control ADC*

Each Beetle readout hybrid features a PT1000 resistive thermometer, which can be read out by its associated Digitizer Board. This is done via a DCUF slow control ADC [9]. After installation of the Service Boxes in the detector, all ADC readouts showed an oscillating odd-even behaviour (Fig. 8).

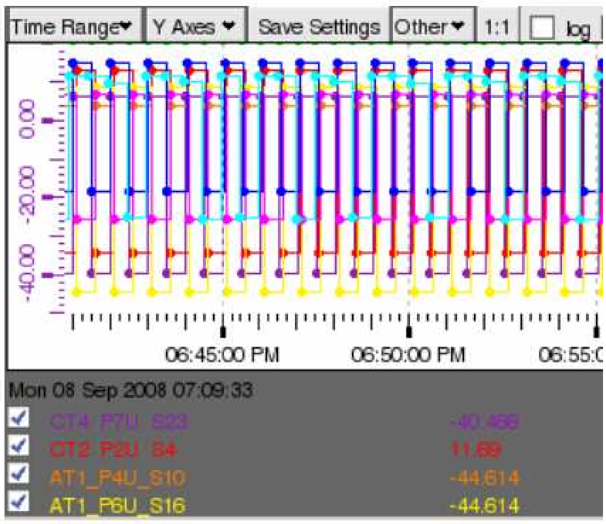

Figure 7: oscillating values from the DCUF slow control ADC

The source of this behaviour was determined to be an overvoltage condition on one of the other ADC input channels. An incorrectly dimensioned resistive divider resulted in an input voltage of 3.8 V, which is beyond specifications for a 2.5 V powered ADC. Once this resistive divider was corrected the DCUF readout worked as designed. The change of dividers has only been done for some Digitizer Boards corresponding to selected locations in the detector as this problem was understood only very late in the commissioning process. As these are non-critical readings, the dividers will be changed over time during normal maintenance and board replacements.

D. *Pressfit Connectors*

Another problem encountered during commissioning in the experiment involved the used ‘Pressfit’ mounting procedure for the backplane connectors. Being an industrial standard for solderless connector mounting, it was initially believed to be adequate for use in the Service Box backplanes. In this through-hole technology variant, the board holes are tightly specified to provide an electrical and mechanical contact to a socket pin which implements a spring-like design. However some protruding pin tips got bent during delivery of the backplanes which compromised the spring tension and resulted in electrical contact failure. Finally, suspicious contacts were resoldered manually to ensure a proper mechanical and electrical contact.

E. *Voltage regulators*

After installation in the detector, immediate commissioning tests for the electronics systems started. It was however determined that for some readout sections no programming of the frontend chips was possible. Other frontend chips could be programmed but failed to generate increased noise in the readout chain indicating a working preamplifier with sensor capacitance attached. This behaviour was caused by a failure of radiation tolerant low-voltage regulators [10] (either digital or analogue supply line) which consequently had to be replaced. Although the failure mechanism is still under investigation, it is likely related to the impedance of the 8 m long cables, which connect the Service Boxes including the regulators to the readout hybrids. Being already installed in the detector, these cables were not part of final burn-in tests of the complete Service Boxes, where such a problem would have been easily spotted. Interestingly, the regulators also signalled an overcurrent condition on their respective monitoring pin, despite the current being only 30% of the maximum rated current.

F. *Power line oscillations*

During first trials with the maximum trigger rate of 1.1 MHz, several Service Boxes on the Cryo side of the TT subdetector reduced their current consumption by about 10 %. This reduced current was still present when stopping triggers again. The only way of restoring the current to standard levels was a complete shutdown of the low-voltage supply followed by a restart. This effect was not seen on either the Access side of the TT subdetector nor in the complete IT subdetector. The final source for this behaviour was later determined to be large (> 2 Vpp) voltage oscillations on the low voltage supply line between the MARATON power supplies [11] and the Service Boxes. Also here it is suspected that the problem is due to the long cables of about 30 m of length, which connect the supplies to the Service Boxes on the Cryo side of the detector. This behaviour was much less pronounced for the Access side of the detector, where power supply cables are about half the length.

Being restricted in volume and board area, only ceramic capacitors were included on the input voltage bus in the Service Box backplanes adding up to about 40 µF of total capacitance. A possibility to suppress the oscillations is to shift the accumulated phase shift of the regulation loop away from a multiple of 2π, which was done by adding 1000 µF electrolytic capacitors externally to each Service Box. Various load tests confirmed the stability of the regulation loop in this configuration, which was eventually extended to the complete TT subdetector.

V. Current Status

Both the TT and IT subdetectors were commissioned during spring and summer 2008. Due to the limited accessibility of the IT subdetector, repairs or exchanges of defective units were delayed until the winter shutdown. Currently, 98 % of the detector is ready for taking physics data. Being much more accessible, repairs for the TT subdetector were possible until a very late stage resulting in a detector being 99 % ready for datataking. These numbers are expected to improve further during the 2008/2009 winter shutdown.

During the LHC injection tests in August 2008, a large amount of data could be recorded for both subdetectors which resulted in initial timing settings and determination of signal-to-noise ratios (Figures 9+10). All results agree with data taken during beam tests in the design phase of the Silicon Tracker development.

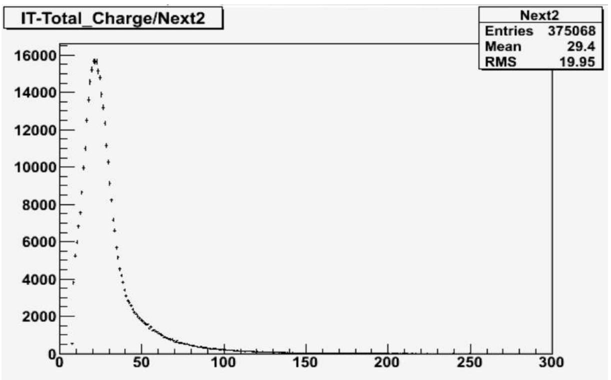

Figure 8: Pulseheight distribution from IT

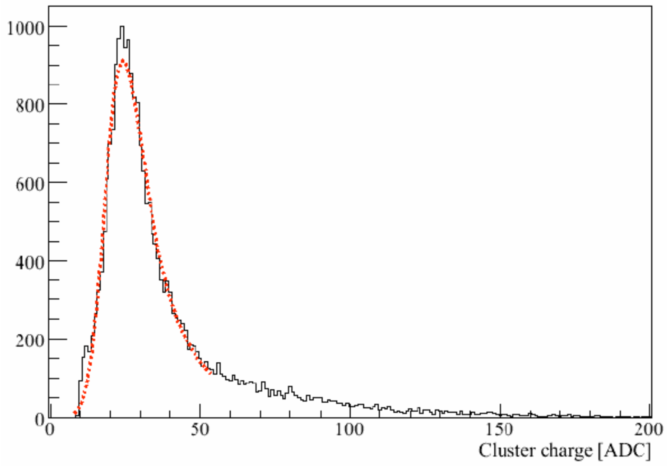

Figure 9: Pulseheight distribution from TT

Preliminary tests looking at the first beam-related data taken during LHC injection tests look promising. Although the occupancy in these events is high, it was possible to find correlations between tracks extrapolated from the VELO and hits in the TT. The observed width of the peak of around 500 µm is compatible with the angular resolution claimed for VELO tracks. Similar correlations have been observed for the IT.

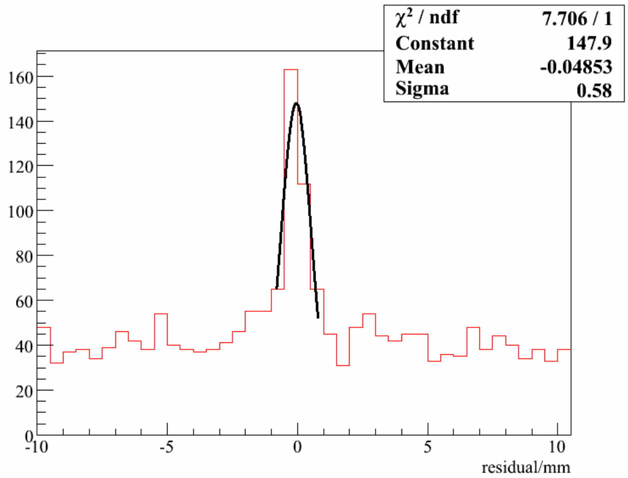

Figure 10: Residual distribution of extrapolated VELO tracks for the TT station.

VI. Conclusion and Outlook

Despite numerous iterations and reviews, several errors were introduced in the design of the LHCb Silicon Tracker. Additional problems were seen later at the system level, after full assembly of the TT/IT components and integration into LHCb. Some of these were simple design mistakes whilst others were the result of underestimating the technical complexity of the chosen approach. Due to time constraints no full system test was made in a beam test. Some of the problems certainly would have been uncovered by such a test.

We believe that only an open sharing of lessons learned can prevent similar mistakes to be done in future developments. Due to the methodical approach and a huge effort by the whole Silicon Tracker collaboration, the Silicon Tracker was completed in time for taking data together with the LHCb detector.

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